On the origin of early type galaxies and the evolution of the interaction rate in the field

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ABSTRACT

Using cosmological N-body simulations of critical (SCDM) and open (Ω=0.3, OCDM) cold dark matter models we have identified dark matter halos which are associated with the progenitors of present day bright early–type galaxies. By following their merging history, we show how early–type galaxies that formed within massive halos at redshift $\simeq 3$ are now preferentially residing in clusters and groups. On the other hand, those that formed through major merging events between redshift 1 and the present have not yet been accreted into larger, virialized structures. This result is in agreement with analytical predictions in hierarchical clustering models. CDM models are able to explain both the ancient and uniform population of ellipticals that dominates in clusters together with the more recent and heterogeneous population of field ellipticals. Predictions for the comoving number density of bright early–type galaxies are given, and are shown to be consistent with the observed luminosity function. We predict that the number density of interacting bright binary galaxies, from which the field population of ellipticals may have originated, is proportional to $(1+z)^{4.2\pm0.28}$ and $(1+z)^{2.5\pm0.42}$ in SCDM and OCDM respectively. This result is consistent with previous analytical estimates and is discussed together with recent observational constraints.

Subject headings: galaxies: formation, ellipticals, cosmology: large scale structure

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1. Introduction

Most elliptical galaxies, are well described by the fundamental plane and show the same dynamical properties (Djorgovski & Davis 1987, Faber *et al.* 1987, Guzman, Lucey & Bower 1993). However, one may also find in the literature a number of publications, including classic work by Larson, Tinsley, & Caldwell (1980), which point out that bright elliptical galaxies residing in clusters have major differences in their stellar populations compared to those residing in the field. Cluster ellipticals show a surprisingly tight color-magnitude and M$gb - \sigma$ relation both at the present (Larson *et al.* 1980, Bower *et al.* 1992) and at higher z (Ellis it et al 1997, Ziegler & Bender 1997). Moreover their colors are consistent with the bulk of their stellar population having been formed at $z > 2$ (Bender, Ziegler, & Bruzual 1996; Ellis *et al.* 1997). The population of field ellipticals shows instead a much larger scatter, indicating a younger age as well as a spread in the time of their last major starburst of at least a few Gyrs (De Carvalho & Djorgovski 1992; Rose *et al.* 1994; Longhetti *et al.* 1997). They also possess a number of features (shells, counterrotating inner disks), believed to be associated with their origin by merger events, which correlate with bluer colors (Schweizer & Seitzer 1992). While deviation from pure ellipsoids, (i.e. boxy or disky isophotes) is not obviously linked to a recent merger event (Governato, Reduzzi, & Rampazzo 1993; Heyl, Hernquist, & Spergel 1994), strongly disky isophotes are interpreted as a sign of recent star formation in a small central gaseous disk, which could have perhaps been accreted through a merger (de Jong & Davies 1996). Finally, Kauffmann, Charlot, & White (1996) point out that a consistent fraction of galaxies with red colors, possibly in the field, have experienced star formation activity at redshifts < 1.

These contrasting results have led to the "nature" or "nurture" hypotheses for the formation of early type galaxies, and specifically of ellipticals (Es). In the former case, star formation occurred at high redshift in a rapid (~ 1 Gyr) burst within protogalactic halos which then quickly coalesced to form galaxies with a dominant spheroidal component; after this event their stellar population evolved passively. In the latter instance, mergers between possibly gas rich galaxies created spheroidal galaxies as remnants (Toomre & Toomre 1972). These two models, can be considered two extreme methods of forming Es within the more general hierarchical clustering framework, where dark matter (DM) halos merge continuously through gravitational instabilities, creating larger and larger structures. This scenario has received strong support from both semianalytical (Baugh, Cole, & Frenk 1996a; Kauffman 1996; Mo & Fukugita 1996) and numerical (Hernquist & Barnes 1991; Hernquist 1993) work. In particular, numerical results show that mergers between gas-rich disk galaxies create systems with luminosity profiles, core structure and kinematics similar to those observed in elliptical galaxies.

By making reasonable assumptions about the DM halos which host the formation of early–type galaxies through the processes just described, we explain the observed environment dependance in the properties of elliptical galaxies within the cold dark matter (CDM) scenario.

2. The simulation dataset

Our simulations followed the evolution of a periodic cube 100 Mpc on a side in both a critical universe (SCDM) ($\Omega_0 = 1$, $h \equiv H_0/100$ km s^{-1} Mpc$^{-1} = 0.5$, $\sigma_8 = 0.7$) and an open (OCDM) universe ($\Omega_0 = 0.3$, $h = 0.75$, $\sigma_8 = 1$). The normalizations were chosen to roughly match the observed cluster abundance. Each simulation was performed using PKDGRAV (Dikaiakos & Stadel 1996, Quinn, Katz, Stadel & Lake 1998), a parallel N–body treecode supporting periodic boundary conditions, and employed 144^3 (~ 3 million) particles with spline softening set to 60 kpc, allowing us to resolve individual halos with present-day circular velocities V_c as low as 100 km s^{-1}with several tens of particles. (In this paper V_c is derived directly from the mass of a given halo, as obtained from the halo finder). Halos were identified at each output using both a standard friends-of-friends method and SKID, a halo-finding algorithm which utilizes local density maxima (a copy can be obtained at http://www-hpcc.astro.washington.edu/tools/).

3. The formation of early–type galaxies

As our simulations include only the effects of gravity on collisionless matter, it is not possible to directly infer the morphological types of galaxies that are thought to form inside DM halos (White & Rees 1978). However, simple considerations based on the expected the high accretion and merging rate , short dynamical friction time-scales and the dynamics of gas cooling at high redshift, allow us to safely assume

that rare, massive halos formed at high redshift will not be able to support a stable stellar disk similar to those observed in present day spirals. In fact analytical considerations (Lacey & Cole 1994, Bower 1991) suggest that major mergers will be very common for galaxy sized halos at high redshift, i.e. close to their typical formation time. These halos will then have a high chance to harbor galaxies with a dominant spheroidal stellar component (Fall & Efstathiou 1980; Toth & Ostriker 1992; Lacey & Cole 1994; White 1997). If those halos are subsequently accreted into groups or clusters, the resultant large potential well prohibits these galaxies from acquiring a gaseous disk through secondary infall of cold gas. Further support is given to this scenario by recent observations of massively star forming galaxies at high z (Yee *et al.* 1996), as well as numerical simulations of merging disk galaxies similar to present day spirals. The simulations show that mergers with a mass ratio of 3:1 or less produce a remnant resembling an elliptical galaxy (Barnes 1996). If the merging event happens at $z < 1$ the galaxy does not have sufficient time to accrete a new gaseous disk (Baugh *et al.* 1996b). Also, at large absolute magnitudes (L> L_*, i.e. large circular velocities) late type galaxies become progressively rarer compared to early type ones (Lake 1990, Heyl *et al* 1996), so strengthening our assumption that halos within the chosen mass range host a luminous early-type galaxy.

Based on these assumptions, we identified the halos in our simulations which were most likely to host early-type galaxies that formed in each of the two distinct ways suggested by the "nature or nurture" picture: i.e. massive halos formed at high redshift ($z > 3$) by the collapse of rare massive peaks and those that formed at $z < 1$ by a "major merger" event, which was defined as the coalescing of two distinct halos with a mass ratio of 3:1 or less. The high-z halos were required to have $V_c > 250$ km s^{-1}, similar to what observed for many high redshift star forming galaxies (Steidel *el al.* 1996) while the range used to identify the low-z merger remnants was 220 km s$^{-1} \leq V_c \leq 320$ km s^{-1}, typical of bright present day Es. Our results do not depend on the details of the velocity cutoffs used, which have been chosen to be representative of those observed in real objects.

Moreover we assume that within our chosen range, the V_c of a given halo can be associated with the V_c of the main galaxy resident within that halo. Galaxies whose stellar populations formed at high redshift (~ 2 or higher) will show very uniform ages, as they all formed when the age of the Universe was just a small fraction of the present. On the contrary a sample of galaxies that formed a consistent part of their star content at $z < 1$, will show a larger spread in colors and derived ages.

It is interesting to note that theoretical models (Baugh *et al* 1997, Governato *et al* 1997) of galaxy formation predict that Lyman break galaxies like those identified at $z \sim 3$ by Steidel and collaborators (1996) will preferentially be residing in halos with circular velocity close to our range of choice. Most likely, the selection criteria used in our work do not define the entire class of halos that could host the formation of early type galaxies and Es in particular; rather, these two populations delimit the extreme ways of forming early-type galaxies within the hierarchical assemblage of cosmic structures. For example S0s could have originated from a variety of different merging histories, such as multiple small accretions of small satellites or fast two body encounters inside a group or cluster environment (Miller 1983, Moore *et al.* 1996; Oemler, Dressler, & Butcher 1997) that lead to short, intense starbursts (Poggianti & Barbaro 1997) and consumed their gas content.

To study the evolution of the population of early type galaxies associated with the identified halos, we examined their subsequent evolution, as made possible by the numerical simulation. To do so we selected halos that, at the present time, contain the halos selected at higher redshift.

We used SKID to identify both high and low redshift halo populations because of its ability over the friends-of-friends algorithm (FOF) to isolate distinct halos even in overdense regions and in the process of merging. Moreover, FOF tends to link together binary halos which would compromise our study. Instead, halos at $z = 0$ were identified using FOF, since we were no longer interested in identifying substructure within larger halos, but rather in defining halo masses within a canonical overdensity $\delta\rho/\rho \sim 178$ relative to the critical density, corresponding to the boundaries of virialized structures. Our results do not change significantly if just one or the other of the two halo-finding algorithms are used, although using solely FOF tends to overestimate the redshift of major mergers since the interacting binaries are "linked together" into a single object sooner than with SKID. FOF also finds fewer high-z objects as it tends to link individual objects that are close to each other and

inside a common overdense region.

Theoretical models of clustering (Bardeen *et al.* 1986) predict that rare peaks at one mass scale, as the halos we selected, should be highly correlated in space. It is interesting to show how well this statement holds in a N-body experiment for actual halos likely to be associated with early-type galaxies, since these will be more closely related to observational data.

It is evident from Fig.1 that for both cosmologies, the majority of halos within our velocity range selected at $z = 3$ or higher now reside in halos with large circular velocities, comparable to groups or galaxy clusters. Visually examining the simulations we find that the halos identified at $z = 3$ are strongly correlated and trace the forming large scale structure. Based on the variance in halo number counts, the total halo population is more clustered than the mass, (by a factor of 2 at a scale of $8h^{-1}$Mpc in the SCDM run). This bias is even higher ($b \sim 4$) for the most massive halos, as those we identified at $z = 3$. They are preferentially located along the biggest filaments (Sathyaprakash, Sahni, & Shandarin 1996). Peculiar motions are preferentially along the filaments, as halos move towards filament intersections were groups and clusters are just beginning to form. This accretion of galaxies, already formed at rather high redshift, continues for a long period of time, even to the present in the critical model. In fact, most of groups and clusters are typically assembled as a single halo at redshift below one.

Our findings for the $z = 3$ selected halos do not imply that the original galaxies have necessarily merged into a single central galaxy by the present time. Tidal stripping and the extremely long time scale for dynamical friction decay (of the order of the Hubble time) should prevent a large fraction of the galaxies from reaching the center of the cluster once it has been stripped of its DM halo. This hypothesis is also supported by recent high resolution simulations of cluster formation (Ghigna *et al* 1997). At the same time, however, the deep cluster potential well would prevent these galaxies from acquiring a substantial gaseous component to fuel star formation at later times. Consequently, we argue that these galaxies are likely be the progenitors of the observed population of old cluster Es.

Recent results (Dickinson 1997, Oemler *et al.* 1997, Smail *et al* 1997) show that even in clusters at $z \geq 0.5$ the elliptical galaxy population is already in place,

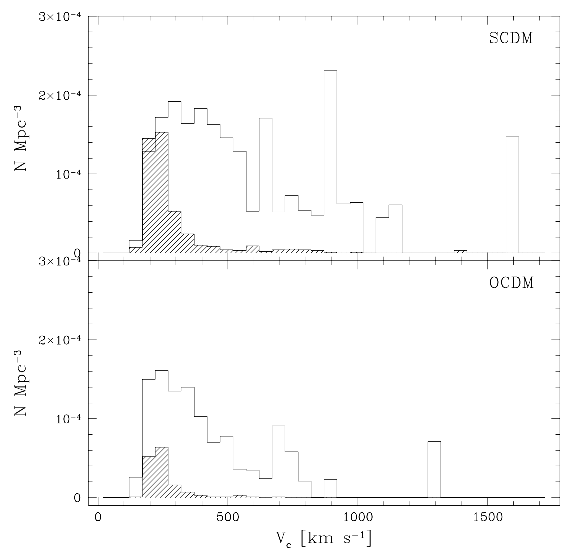

Fig. 1.— Histogram of the comoving number density distribution of early–type galaxies identified at $z = 3$ as a function of the circular velocity of halos that contain them at the present time. The top panel shows results for SCDM and the bottom panel from OCDM. The last bin represents the biggest halo identified at $z = 0$, which contains several tens of halos identified at $z = 3$. The continuous line refers to halos selected at $z = 3$, with 250 km s^{-1} $\leq V_c$. The shaded region refers to halos formed by major mergers between $1 > z > 0$ with circular velocity 220 km s^{-1}$\leq V_c \leq 320$.

showing colors typical of passive evolution and consistent with an origin at z> 2, and so supporting our proposed scenario. Even if the accretion of Es by clusters happened over a large range of z, in parallel with the build up of clusters from smaller structures, this did not create a population of elliptical galaxies in clusters with a large age spread, suggesting that the initial collapse of the parent halos was efficient in turning most of each individual galaxy gas content into stars or expelling it under the form of hot gas.

On the other hand, a significant fraction of the S0 galaxies observed at the present time seems to be lacking in clusters at intermediate z, suggesting a different time scale and principle mechanism for their creation, possibly due to interactions within the cluster environment.

The situation is rather different if we look at the products of major mergers selected between $1 > z > 0$. They now reside in halos of mass comparable to that at their time of formation, indicating that they have not yet been accreted by a larger structure. The great majority of them reside in what is generically referred to as "the field", i.e regions of density close to the average one, implying that merger remnants are much less biased compared to the general mass distribution. Even these halos also formed within a very complex environment made of filaments and planes; however gravitational clustering did not have enough time to act and move them into larger structures, as was possible for halos selected at $z = 3$.

It is interesting to compare the number density of our selected halos with existing observational data. The luminosity function obtained by Heyl *et al.* (1996) gives a number density of 2×10^{-3} Mpc^{-3} for "red E" galaxies with $M_{\rm bj} < -19$, the magnitude cut corresponding to the circular velocity associated to our lower limit. The Marzke *et al.* (1994) luminosity function (based on Zwicky's magnitudes) gives a comoving number density of E+S0 in the same luminosity range of 1.8×10^{-3}Mpc^{-3}. If we sum the halos selected at $z = 3$ with all major mergers between $1 > z > 0$ we obtain a number density of 2.8×10^{-3} Mpc^{-3} and 1.4×10^{-3} Mpc^{-3} for SCDM and OCDM respectively. In both cosmologies early–type galaxies identified at high z are much more numerous than those that were formed at lower redshift. In our scenario recent merger remnants would represent only 16% (for SCDM) and 10% (for OCDM) of the present day population of elliptical galaxies.

Considering the large uncertainties in both our schematic models and the observational data (due for example, to the size of the volume studied and hence of the small range of environments sampled) there is a good agreement, within less than a factor of two, between theory and the observed numbers. A better match could be found for individual models but this would require to arbitrarily adjust the velocity cutoff we used to select halos and/or the magnitude cut in the luminosity function at the present time. Overall, though, the agreement between the observed number density of Es and the number density of the selected halos in the simulations strongly supports the hypothesis that we are selecting DM halos associated with galaxies dominated by a spheroidal component.

These results illustrate that two different and possibly extreme populations of halos that should host early-type galaxies are indeed very segregated in space, consistent with both analytical predictions for the clustering of halos and with observational evidence for Es. In this scenario, cluster and field Es would naturally show different age properties. Galaxies that most probably formed their stellar population at high redshift ($z > 2$) would have uniform colors, consistent with a similar age of formation followed by passive evolution. Es formed by late mergers would instead have a larger spread in the age, corresponding to their latest major starburst. In agreement with observations, only a few of this galaxies now reside in groups and clusters. Hence, CDM models provide a consistent framework capable of explaining the differences in age and properties between the bulk populations of cluster Es (ancient and with uniform age for their stellar component) and field Es (younger and with a larger age spread).

4. The interaction rate of binary systems

There is strong observational evidence (Driver *et al.* 1995, Glazebrook *et al* 1995) that the number of interacting systems grows rapidly with look-back time. New data from the Hubble Deep Field (Abraham *et al.* 1996; Van Den Bergh *et al.* 1996) and recent redshift surveys (Patton *et al* 1996) make it possible to measure their number and determine whether the Universe was in the past more dynamically active at galactic scales. The data suggest a strong evolution in number density proportional to $(1+z)^{2.8\pm0.9}$ (Patton *et al.* 1996) or even steeper: ($\propto (1+z)^{4.0\pm2.5}$ in Zepf & Koo (1989)) or $\propto (1+z)^{3.4\pm1.0}$ as suggested by

the number of close galaxy pairs (Carlberg, Pritchet & Infante 1994).

The exact value for this trend is very important, given its consequences on the evolution of the galaxy population and on galaxy counts (Ellis 1997, Roche *et al.* 1996, Baugh *et al.* 1996b). Similar trends are found in samples of radio-quiet QSOs (Boyle *et al.* 1993) and IRAS-selected galaxies. Fig.2 plots the rate of formation of merger remnants for SCDM and OCDM models. Vertical error bars represent statistical uncertainties due to the finite size of the sample, and the horizontal span the time interval between successive outputs (of the order of one Gyr), effectively our bin size. We find $(1+z)^{4.2\pm0.28}$ for SCDM and $(1+z)^{2.5\pm0.42}$ for OCDM respectively, while the rate at $z = 0$ is similar and close to $10^{-8}\mathrm{Myr}^{-1}\mathrm{Mpc}^{-3}$. Merging rates obtained from this work are in good agreement with previous analytical predictions by Carlberg (1990). Our selected sample of halos should host luminous galaxies, which in turn should be preferentially selected in samples containing higher redshift galaxies. As suggested by detailed numerical simulations, they should form a luminous starburst remnant when the galaxies inside each halo actually collide and merge (Mihos & Hernquist 1994). While taken at face value this result would seem to slightly favor a low omega model, were the interaction rate is lower and the redshift dependency flatter, it is difficult to translate our results into a strong number density prediction for a specific class of observed objects. For example, Lavery *et al.*(1996) suggest a rate of interactions of $(1+z)^{4.5}$ based on the number density of ring galaxies. In fact it is not yet clear how QSOs and starburst galaxies, of which the number density is found to increase with redshift, are directly related to interactions and mergers. However our results suggest a general agreement of CDM models with the observed trend. It is interesting to note that, due to the steeper increase at high redshift, and contrary to what would be naively expected, the mean redshifts for this specific class of mergers is higher in the SCDM sample than in the OCDM one. However, the longer age stretch in the OCDM universe compensates for this, once measured in look back time.

In the hierarchical clustering model, collapse begins with smaller (i.e. galaxy-sized) scales and proceeds to larger and larger masses. Hence, the observed increase in galactic activity in the past is a natural by-product of this model, with the number of interacting galaxies increasing with redshift. In the present-day universe, most of the galaxy-sized perturbations have collapsed, and it is now cluster-scale objects with masses of order $10^{14}\mathrm{M}_{\odot}$ or higher that are being assembled. Clusters are indeed observed to be forming and accreting large quantities of matter at the present time, but there is no evidence of an increase in their formation rate looking at high redshifts (Eke, Cole, & Frenk 1996). The ability to predict this very diverse, time-dependent behavior between objects at different mass scales can be considered a major success of the hierarchical clustering model and specifically of CDM.

5. Discussion

In this paper we show how hierarchical clustering models, namely CDM, naturally account for the the different properties of cluster and field Es. In particular they account for the high average value and the small scatter in the ages measured for cluster Es as opposed to the younger age as well as a larger scatter around the average value found for Es in the generic field environment.

Numerical simulations show, in accordance with theoretical predictions, that spatial correlation of the higher peaks in the density field (Bardeen *et al.* 1986) naturally explains the fact that the objects that collapse at high redshift are now very clustered and contributed to the build up of galaxy clusters. Instead, galaxy sized halos collapsing at later times show a much less degree of clustering and are preferentially found in field regions.

In fact, after making the hypothesis that stellar population ages are tied to the collapse times of the parent DM halos, we are able to show that early-type galaxies that formed their stellar population at high redshift in massive DM halos are now in clusters, while those formed through major mergers at $z < 1$ have not been accreted into larger structures. As these recently formed galaxies do not end up into dense environment, elliptical galaxies in clusters should show, for the great majority, colors consistent with a very ancient stellar population. This is consistent both with observations and with predictions from semianalytical models of galaxy formation (Kauffman 1996). The small scatter in age for cluster Es arises naturally from the fact that at high z, when they formed the majority of their stellar content, the age of the Universe was a small fraction of the present time. Apparently, even if these galaxies were accreted into cluster at different times, subsequent to their for-

mation, this delayed accretion did not create a large scatter in the age of their stellar populations.

We further demonstrate that within the CDM framework the interaction rate in binary galactic systems increases rapidly in the past, consistent with observations. Recent techniques based on line strength indices are able to evaluate the epoch of the last starburst with a precision of a few Gyrs (Dorman & O'Connel, 1996; Bressan, Chiosi, & Tantalo 1996; De Jong & Davies 1997; Longhetti *et al.* 1997) and disentangle the time evolution from metal abundances of the stellar populations. These methods will prove invaluable in tracing the origin of early type galaxies in different environments and will provide a larger database to test theories of galaxy formation. Future detailed simulations which include hydrodynamics and star formation processes will be able to make more robust and quantitative predictions about the origin and evolution of galaxies within the CDM scenario.

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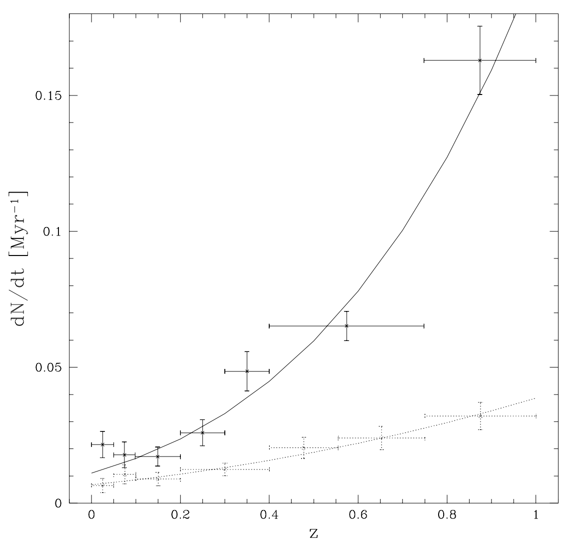

Fig. 2.— Rate of formation of major mergers between $0 < z < 1$ as a function of redshift for SCDM (solid) and OCDM (dotted). Lines are best fits in the form $(1+z)^{\alpha}$, where $\alpha = 4.2$ for SCDM and 2.5 for OCDM.